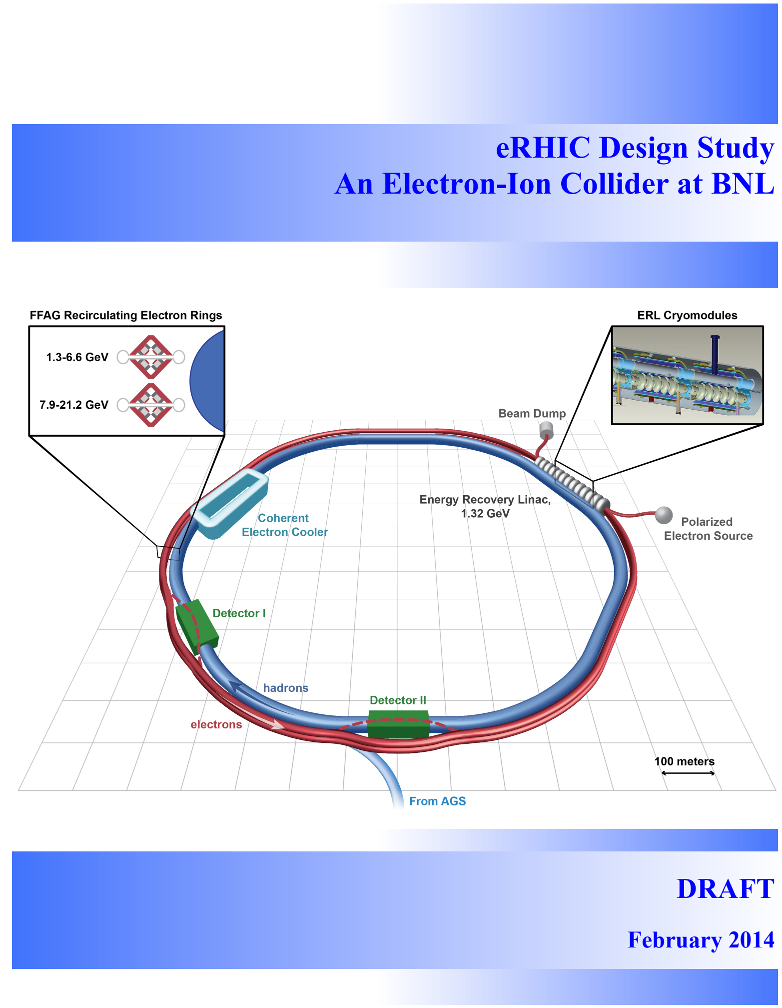
Facility Overview BNL

T. Roser for the eRHIC design team

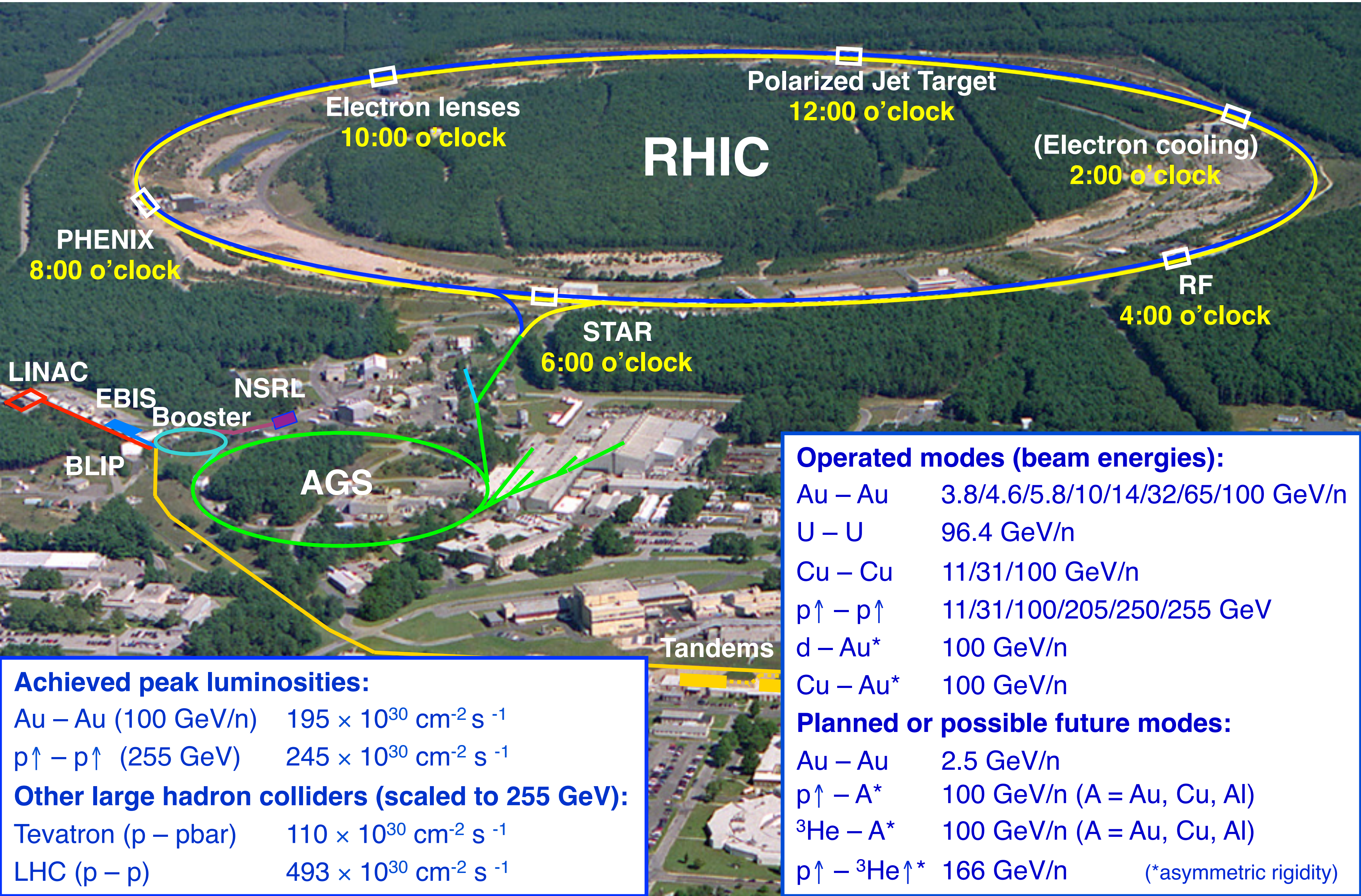


- RHIC facility performance
- eRHIC design
- eRHIC R&D
- eRHIC preliminary schedule and cost estimate

BROOKHAVEN
NATIONAL LABORATORY

Thomas Roser
EICAC meeting
February 28, 2014

RHIC – a High Luminosity (Polarized) Hadron Collider



Achieved peak luminosities:

Au – Au (100 GeV/n)	195×10^{30} cm^{-2} s^{-1}
p$\uparrow$ – p$\uparrow$ (255 GeV)	245×10^{30} cm^{-2} s^{-1}

Other large hadron colliders (scaled to 255 GeV):

Tevatron (p – pbar)	110×10^{30} cm^{-2} s^{-1}
LHC (p – p)	493×10^{30} cm^{-2} s^{-1}

Operated modes (beam energies):

Au – Au	3.8/4.6/5.8/10/14/32/65/100 GeV/n
U – U	96.4 GeV/n
Cu – Cu	11/31/100 GeV/n
p$\uparrow$ – p$\uparrow$	11/31/100/205/250/255 GeV
d – Au*	100 GeV/n
Cu – Au*	100 GeV/n

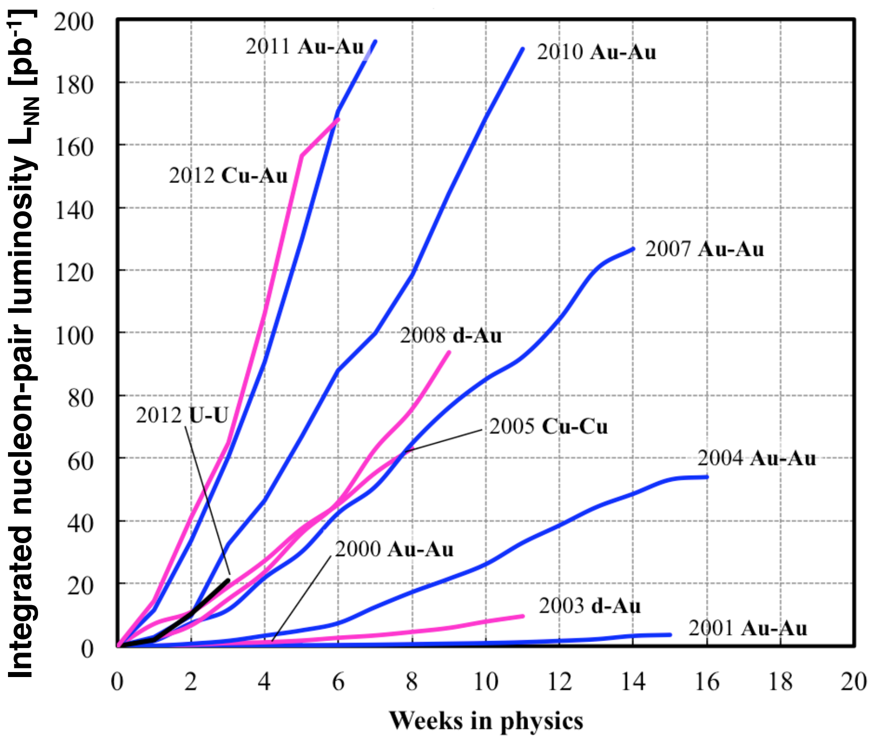
Planned or possible future modes:

Au – Au	2.5 GeV/n
p$\uparrow$ – A*	100 GeV/n (A = Au, Cu, Al)
^{3}He – A*	100 GeV/n (A = Au, Cu, Al)
p$\uparrow$ – ^{3}He$\uparrow$*	166 GeV/n

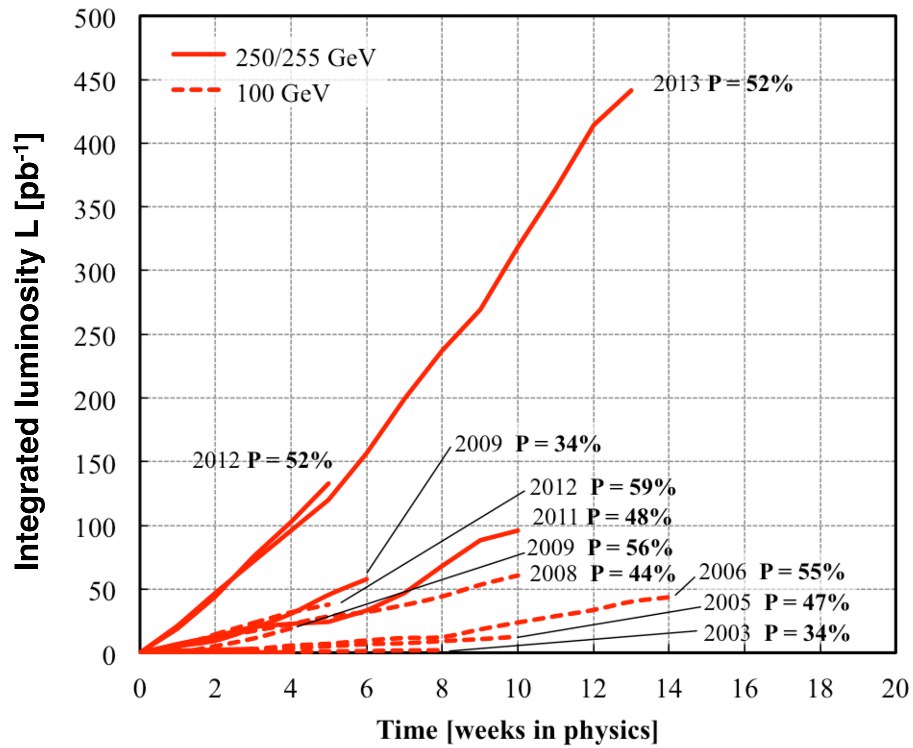
(*asymmetric rigidity)

RHIC Integrated Luminosity and Polarization (RHIC II performance!)

Heavy ion runs



Polarized proton runs

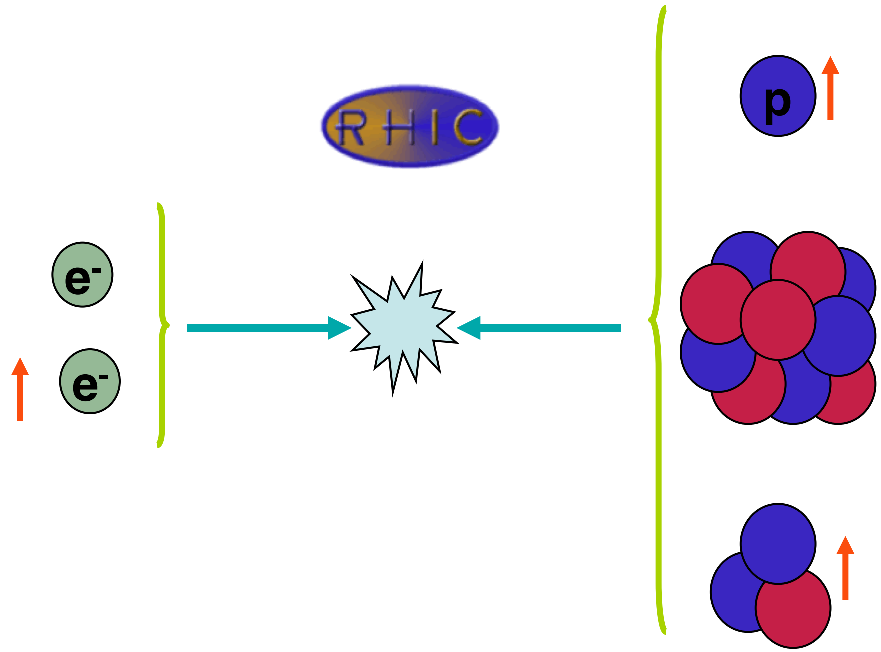


- Further upgrades:
  - 56 MHz srf system to reduce vertex length (commissioning this RHIC run)
  - Electron lenses to ~ double pp luminosity (engineering test this RHIC run)
- Facility availability is typically well above 80% (FY12: 85%; FY13: 84%)
- Calendar time-in-store (physics) is about 60% (~100 hours per week)

eRHIC: QCD Facility at BNL

Add an electron accelerator to the existing $2.5B RHIC
including existing RHIC tunnel and cryo facility

Unpolarized and 80% polarized electrons:
15.9 GeV
(6.6 – 21.2 GeV)

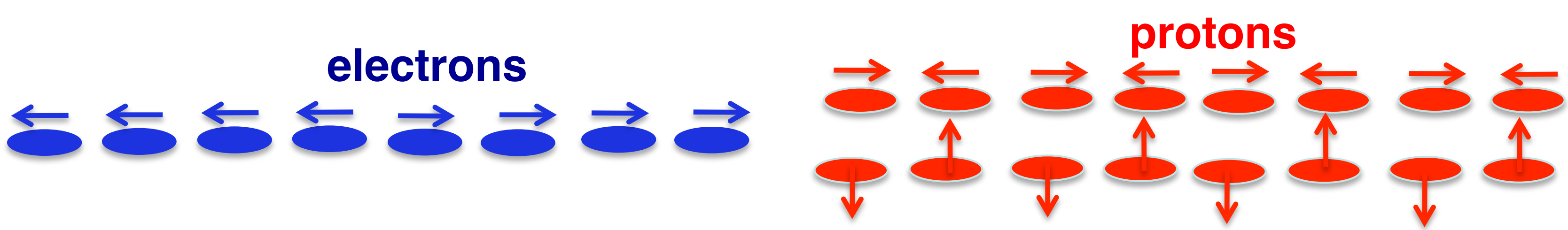


70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

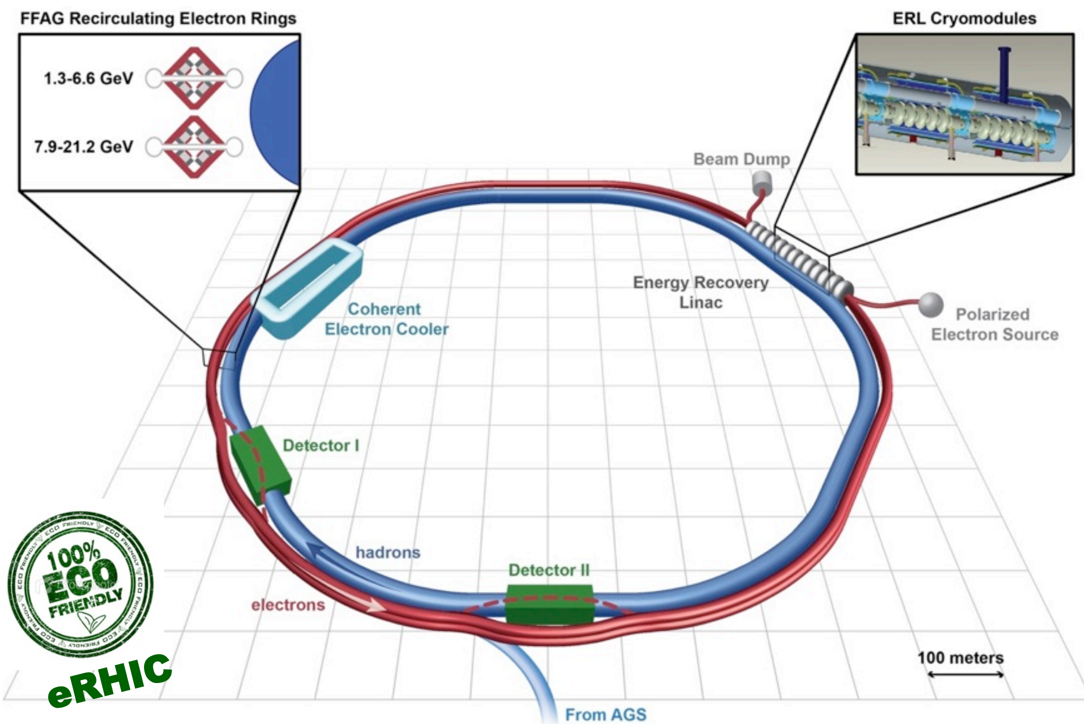
Center-of-mass energy range: 30 – 145 GeV
Any polarization direction in electron-hadron collisions



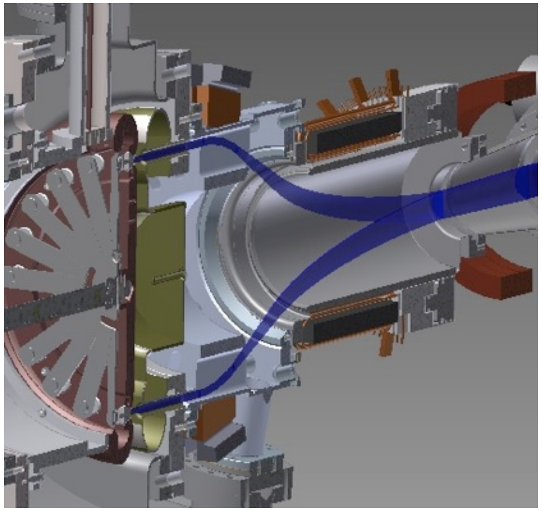
*** It is possible to increase RHIC ring energy by 10%**

eRHIC design

- Up to 21.2 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single collision of each electron bunch allows for large disruption, giving high luminosity and full electron polarization transparency
- Accelerator R&D for highest luminosity: High current (50 mA) pol. electron gun (Gatling gun); High average current ERL with FFAG passes; Coherent electron cooling of hadron beam
- ERL with 1.32 GeV SRF Linac and two FFAG recirculating rings (1.33 – 6.62 GeV; 7.94 – 21.16 GeV) allow for full luminosity (> 10^{33} cm^{-2} s^{-1}) up to 15.9 GeV and reduced luminosity up to 21.2 GeV
- Nov. 2013 C-AD MAC review: "The MAC congratulates the eRHIC design team for its ingenious and novel use of the FFAG concept."



50 mA polarized electron gun (Gatling gun)



Evolution of electrons in ERL with NS-FFAG

- Polarized electron bunch starts in one cathode of Gatling Gun
- Acceleration in SRF CW cavity to 12 MeV and first injection into 1.32 Linac
- After Linac, at 1.33 GeV, spreader brings electron bunch onto correct orbit correct optics functions for first pass in low energy FFAG ring
- Combiner matches optical functions to Linac and brings orbit to center line
- After second pass through Linac, at 2.65 GeV, a second line of spreader matches to second turn in low energy FFAG.
- Continue for total of five turns and six passes through Linac (7.94 GeV)
- Spreader now matches electron bunch to first pass through high energy FFAG ring
- Continue for six turns through high energy FFAG and 1.32 GeV Linac, which brings energy to 15.9 GeV
- On highest energy pass through high energy FFAG beam is being split off for collision with hadron beam in detector.
- The collision occurs with a crossing angle of 10 mrad. The electron and hadron bunch are each rotated by 5 mrad using crab cavities for head-on collisions.
- The electron bunch is then delayed by 180 degrees to enter Linac on decelerating phase
- After exactly retracing the same path as during acceleration (7 passes through the high energy FFAG, 5 passes through the low energy FFAG and 12 decelerating passes through the Linac) the electron bunch is getting dumped at 12 MeV.

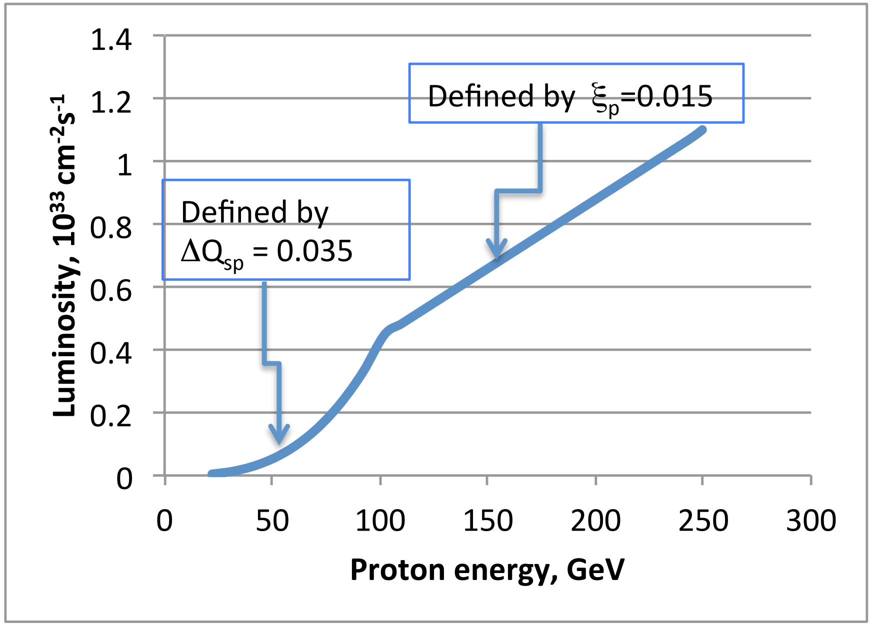
eRHIC beam parameters and luminosities

	e	p	$^{3}He^{2+}$	$^{197}Au^{79+}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		122.5	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms norm. emittance, μm		0.27	0.20	0.20
Electron rms norm. emittance, μm		31.6	34.7	57.9
Beta*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Electron beam disruption		2.8	5.2	1.9
Space charge parameter		0.006	0.016	0.016
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} cm^{-2}s^{-1}		1.5	2.8	1.7

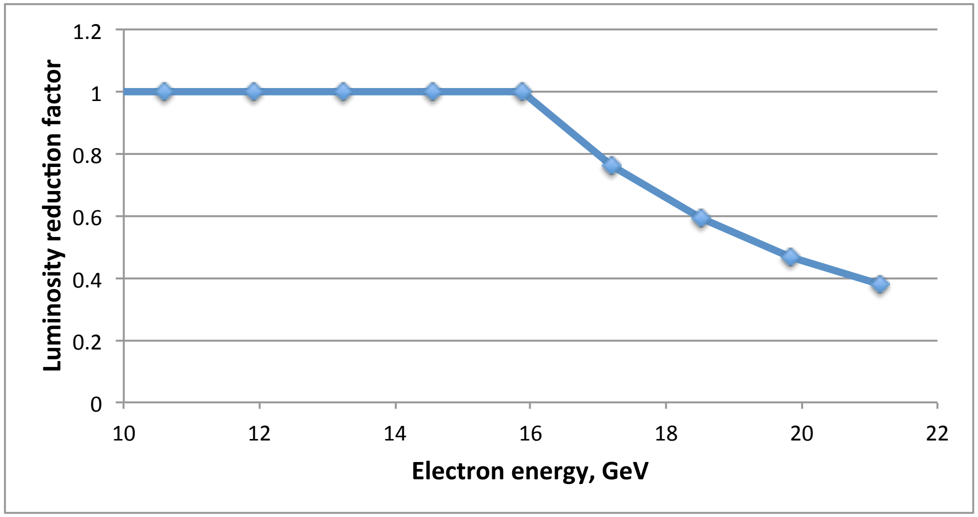
- 15% of the hadron beam intensity presently achieved in RHIC: allows to operate with present RHIC vacuum chamber (e.g. no coating is needed) and without space-charge compensation at lower hadron energies.
- With vacuum chamber coating a 10-fold higher luminosity can be reached.

Luminosity versus beam energy

- Luminosity versus hadron beam energy
  - For 15.9 GeV electron energy or less
  - Limited by hadron beam-beam parameter above 100 GeV and space charge below 100 GeV

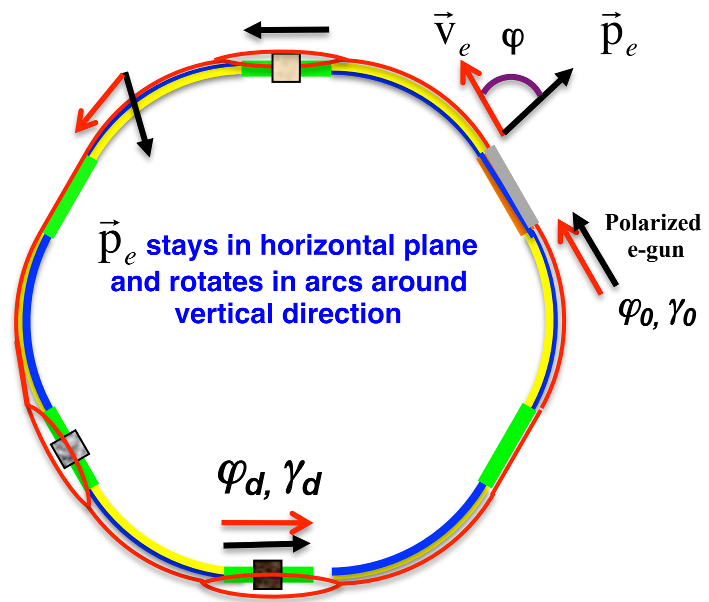


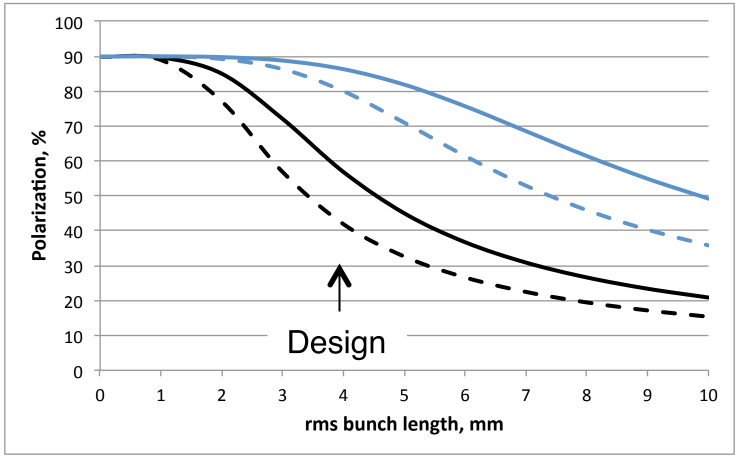
- Luminosity versus electron beam energy
  - Limited by maximum SR power of 12 MW above 15.9 GeV



Electron polarization in eRHIC

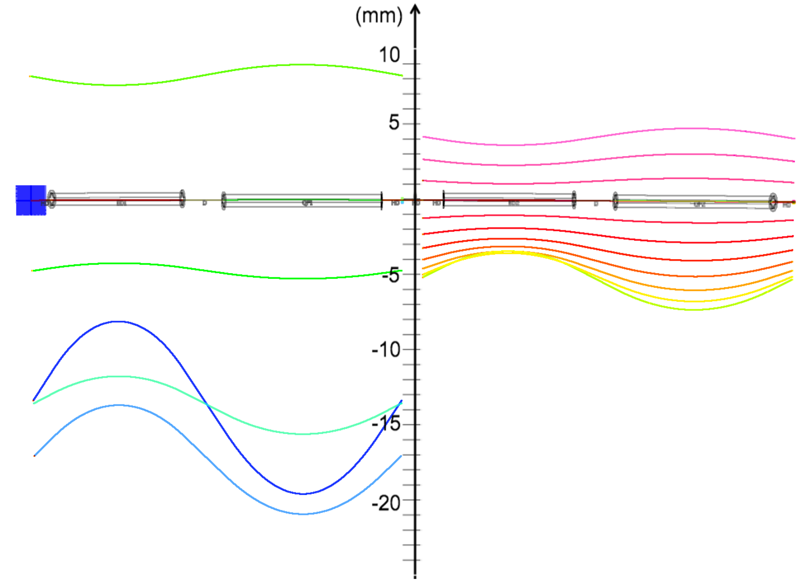
- Only longitudinal polarization is needed in the IPs
- 90% longitudinally polarized e-beam from DC gun with strained-layer super-lattice GaAs-photocathode with polarization sign reversal by changing helicity of laser photons
- Integer number of 180-degrees spin rotations between gun and IPs
- Depolarization due to beam energy spread: 6% (11%) for 15.9 GeV (21.2 GeV) with harmonic cavities to compensate the energy spread from the main linac
- With the linac energy of 1.32 GeV the polarization is longitudinal at both IPs.

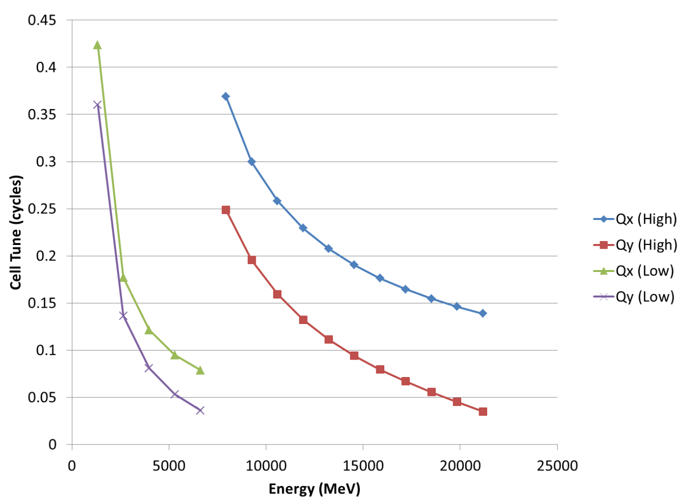


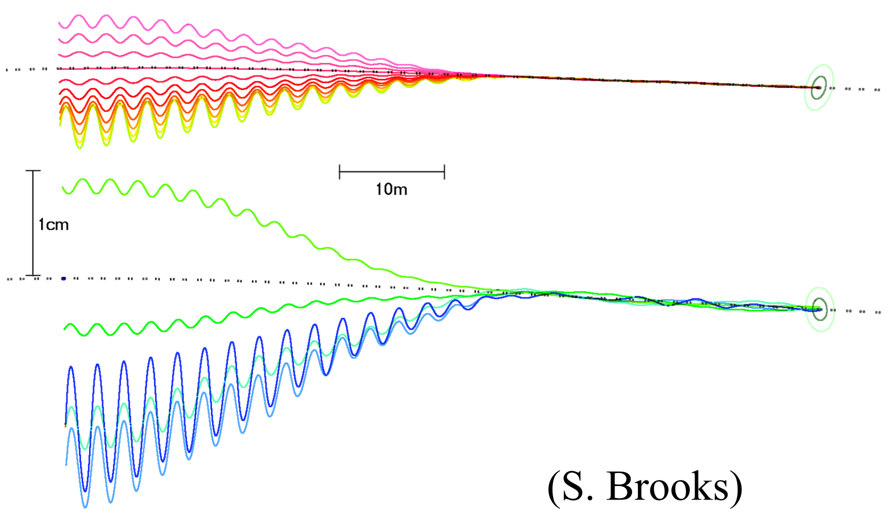


FFAG recirculation arcs

- Non-scaling (tune changes) Fixed-Field Alternating Gradient beam transport (D. Trbojevic)
- Very strong focusing channel can transport large energy range
- Small quadrupole offsets bend the beams adiabatically if bend radius is much larger than cell length
- 2 FFAG rings: 1.33 – 6.62 GeV, 7.94 – 21.16 GeV
- Permanent magnets possible



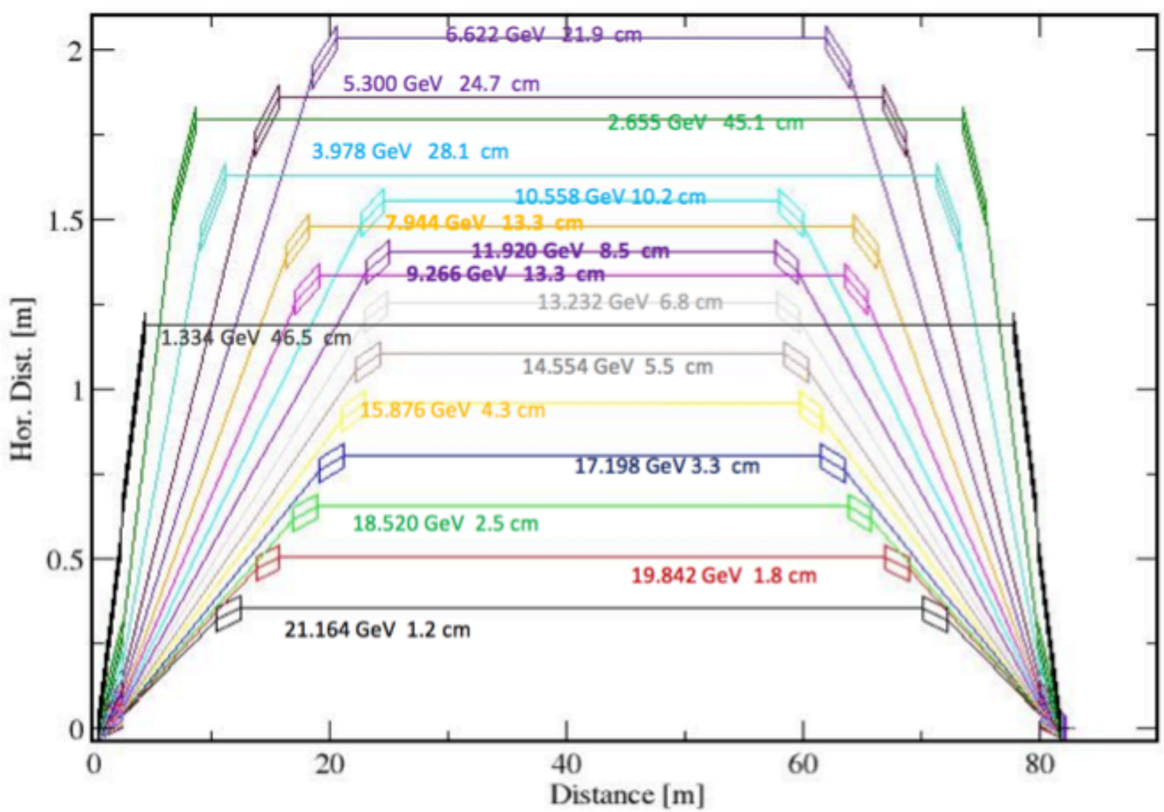




(S. Brooks)

Beam spreader/combiners on either side of Linac

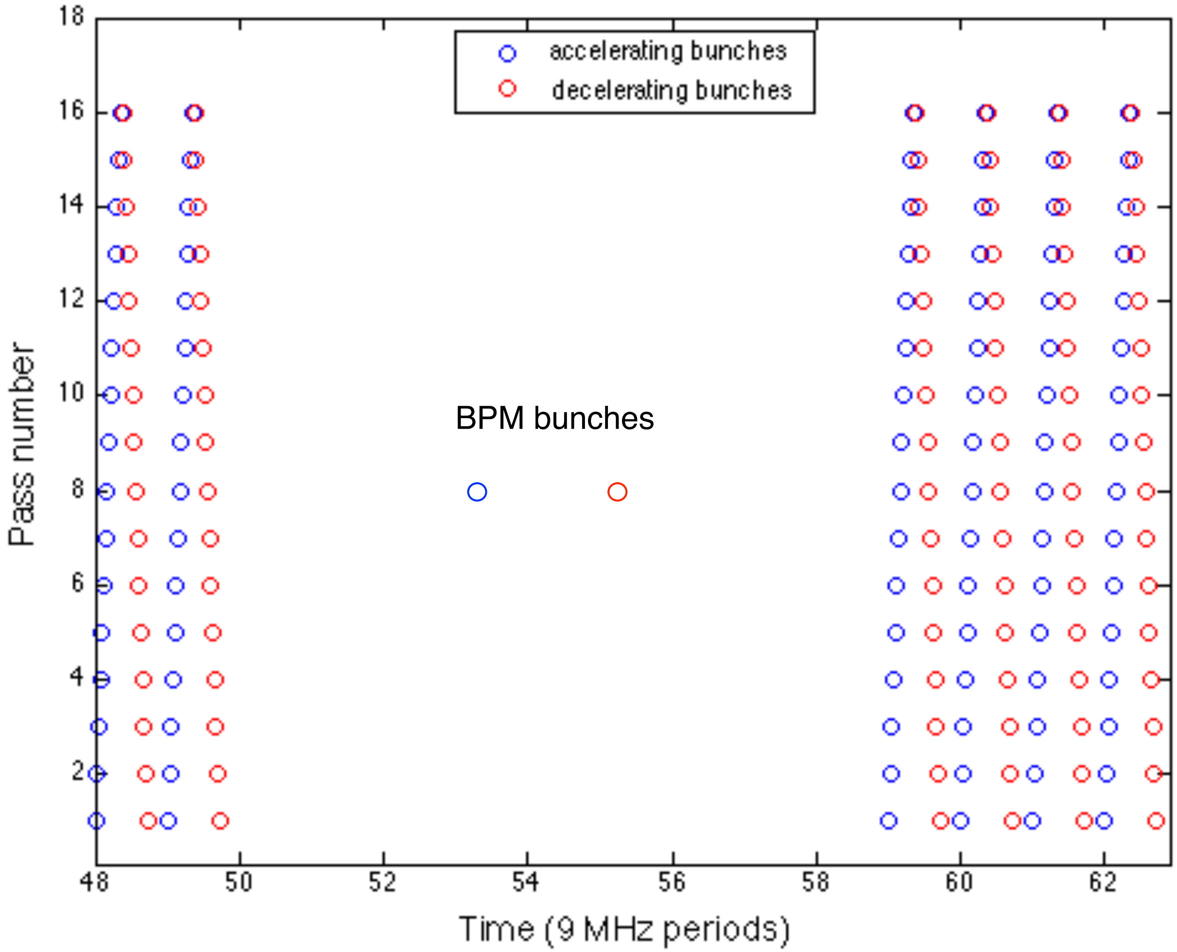
- Separate/combine the 16 beams with different energies between FFAG arcs and CW Linac
- Used to match the beam optics of linac and FFAGs and for rough and fine time of flight adjustments
- Vertical chicane for time-of-flight adjustment not shown



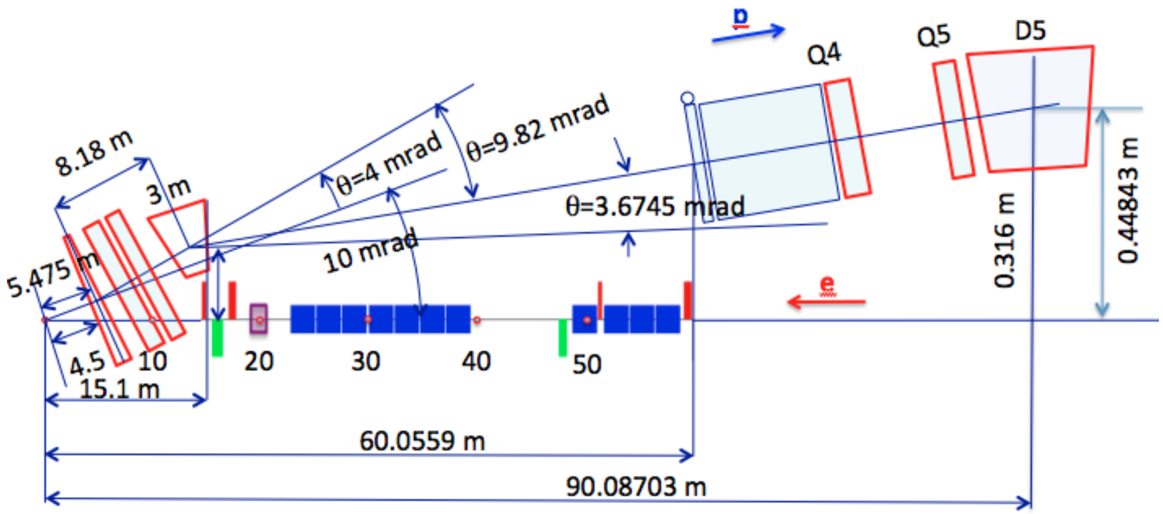
(N. Tsoupas)

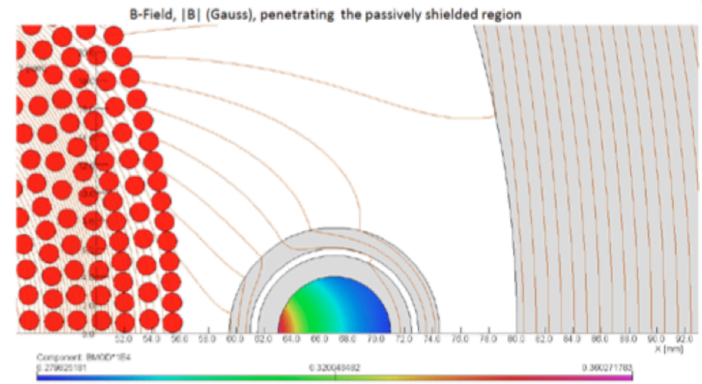
e-Beam bunch pattern

- ~ 900 ns gap to eliminate ion accumulation
- Every 16 RHIC revolution periods inject one bunch into the gap. Its trajectory on the trip to 21.2 GeV and back will be measured by single pass BPM.
- Information from these bunches is used to correct the orbit of all passes

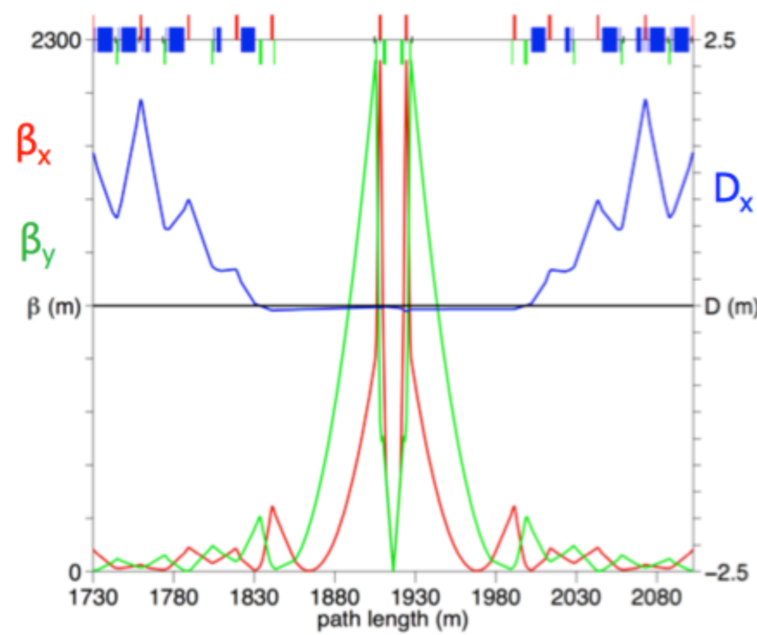


eRHIC high-luminosity IR with β* = 5 cm



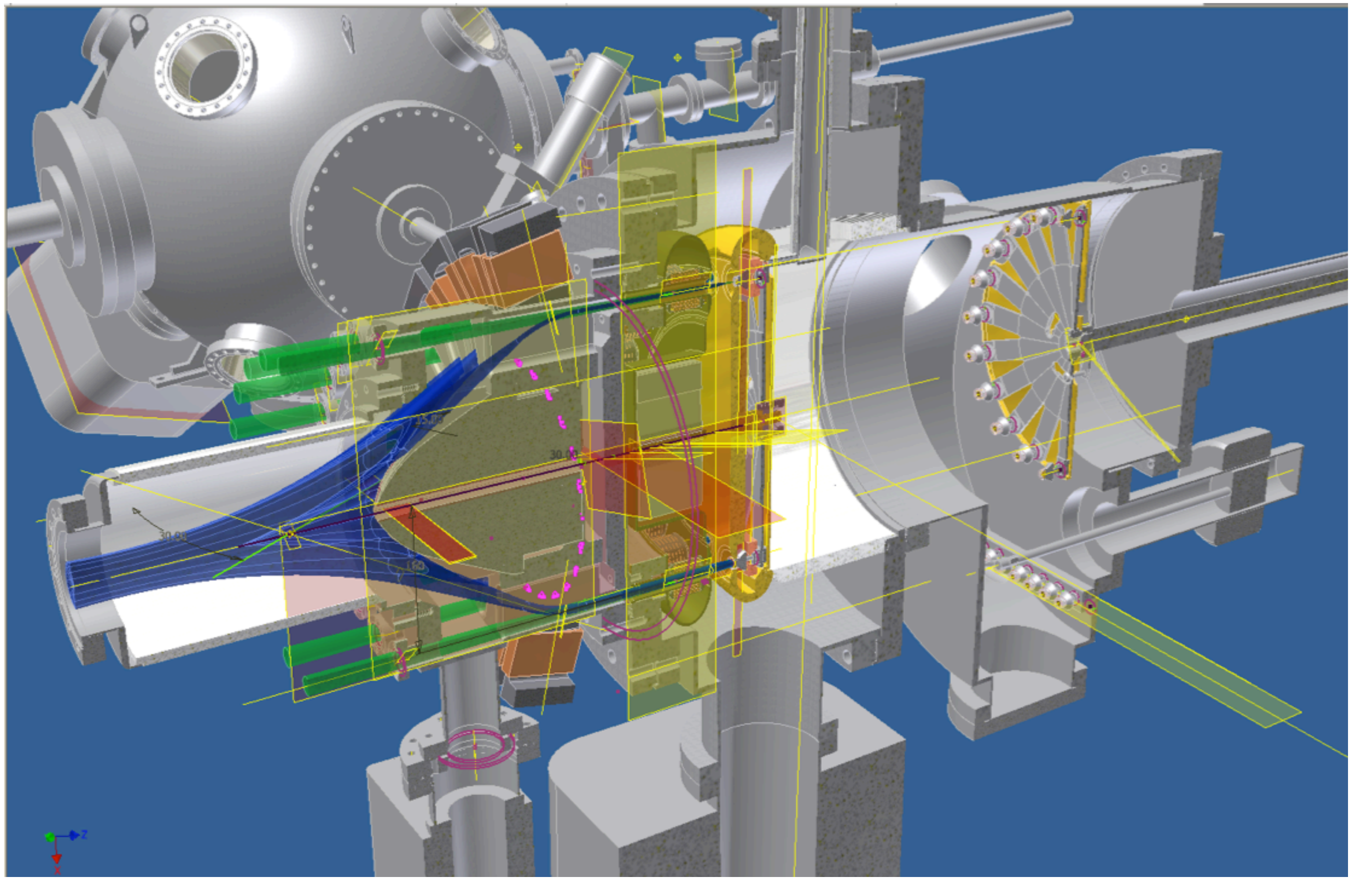


- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs (ATS) to reach beta* of 5 cm with good dynamic aperture
- Combined function triplet with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron beam within 60 m upstream of IP



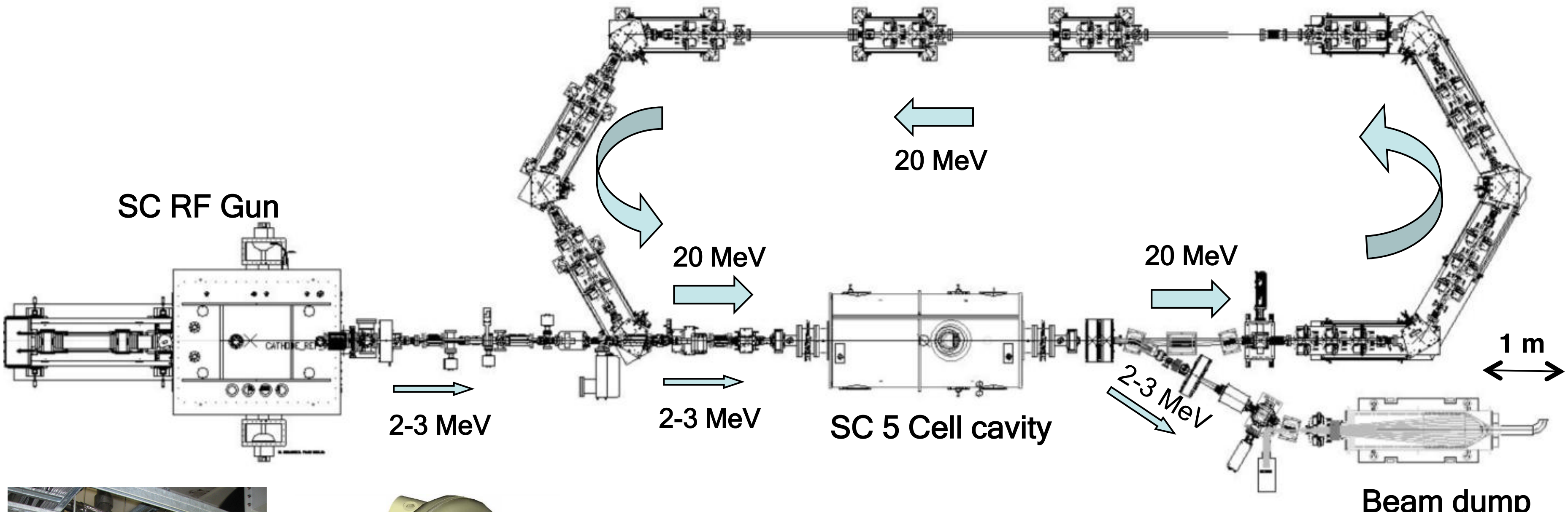
High CW current polarized electron gun

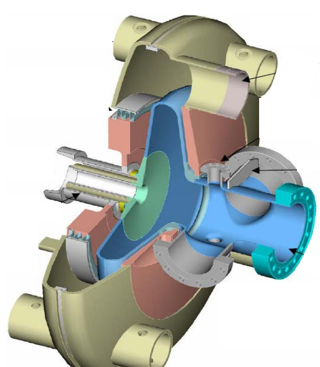
- Matt Poelker (JLab) achieved 4 mA polarized e-beam with good lifetime
- More current with effectively larger cathode area
- Test at MIT with very large cathode area
- Gatling gun: multiple cathodes to effectively increase cathode area
- Gatling Gun Test: twice the current from two cathodes with same lifetime (by end of 2014)



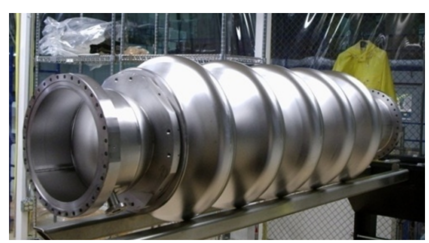
Energy Recovery Linac (ERL) Test Facility

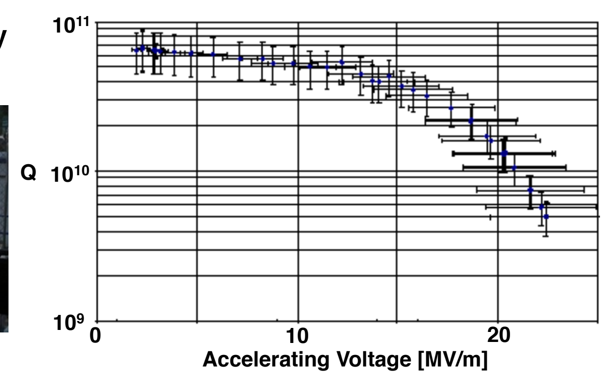
- Test of high current (50 mA, 12 passes eRHIC), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Gun rf tested at 2 MV; beam from gun: April 2014, recirculation: 2015/16
- Gun and cavity will be used for ERL of Low Energy RHIC electron Cooling



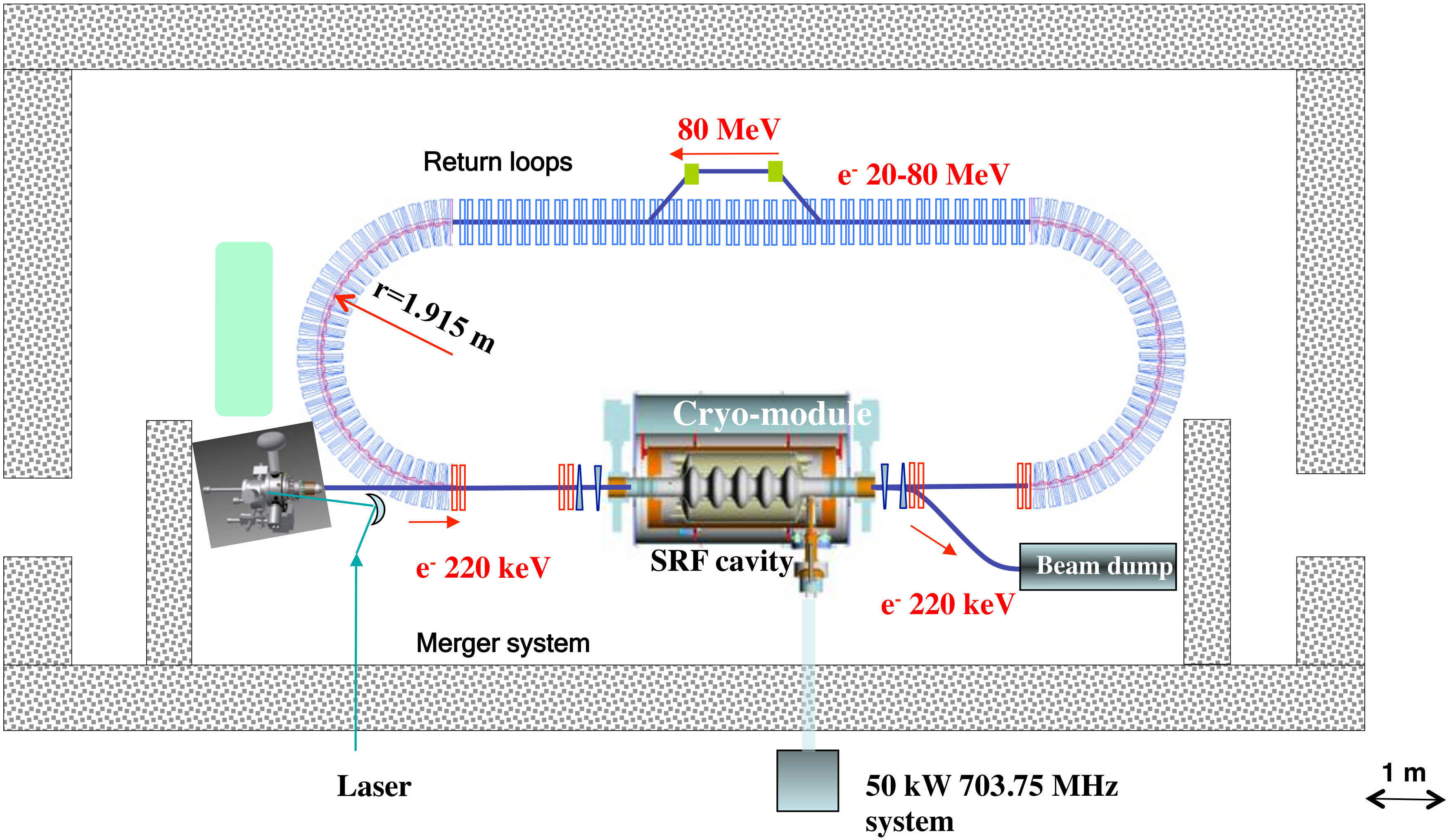


5 Cell SRF "single mode" cavity
Q > 10^{10} @20 MV/m CW





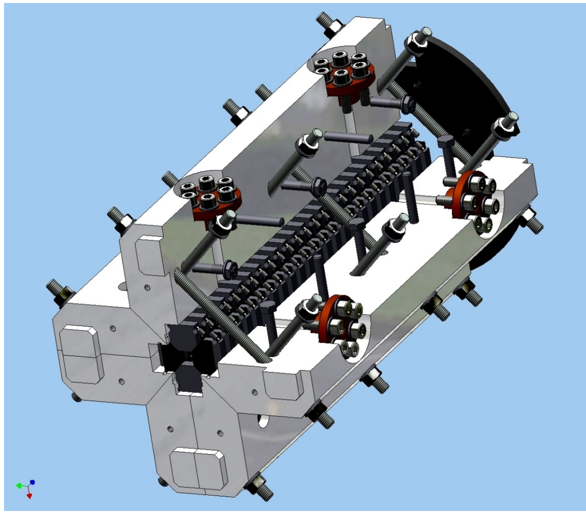
NS-FFAG ERL prototype



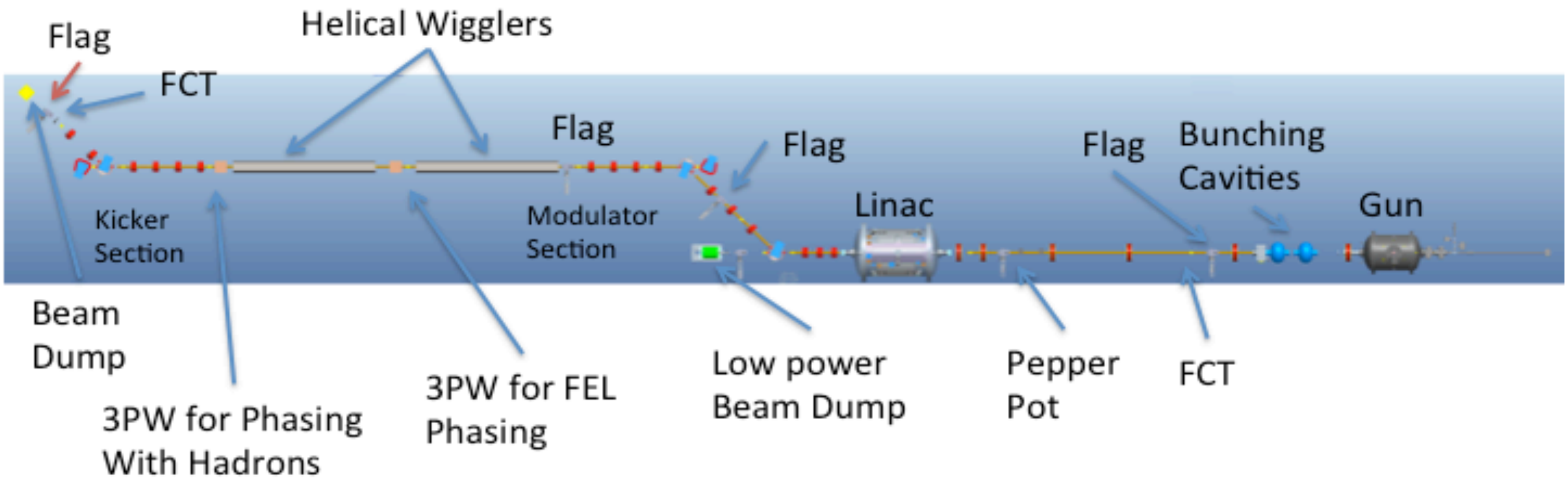
Goal: Prototype eRHIC ERL with Gatling Gun, FFAG permanent magnet arcs, and maybe eRHIC cryo-module.

Coherent electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → 10x reduced proton emittance gives high eRHIC luminosity
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (~ 2015 - 16)



Helical wiggler prototype



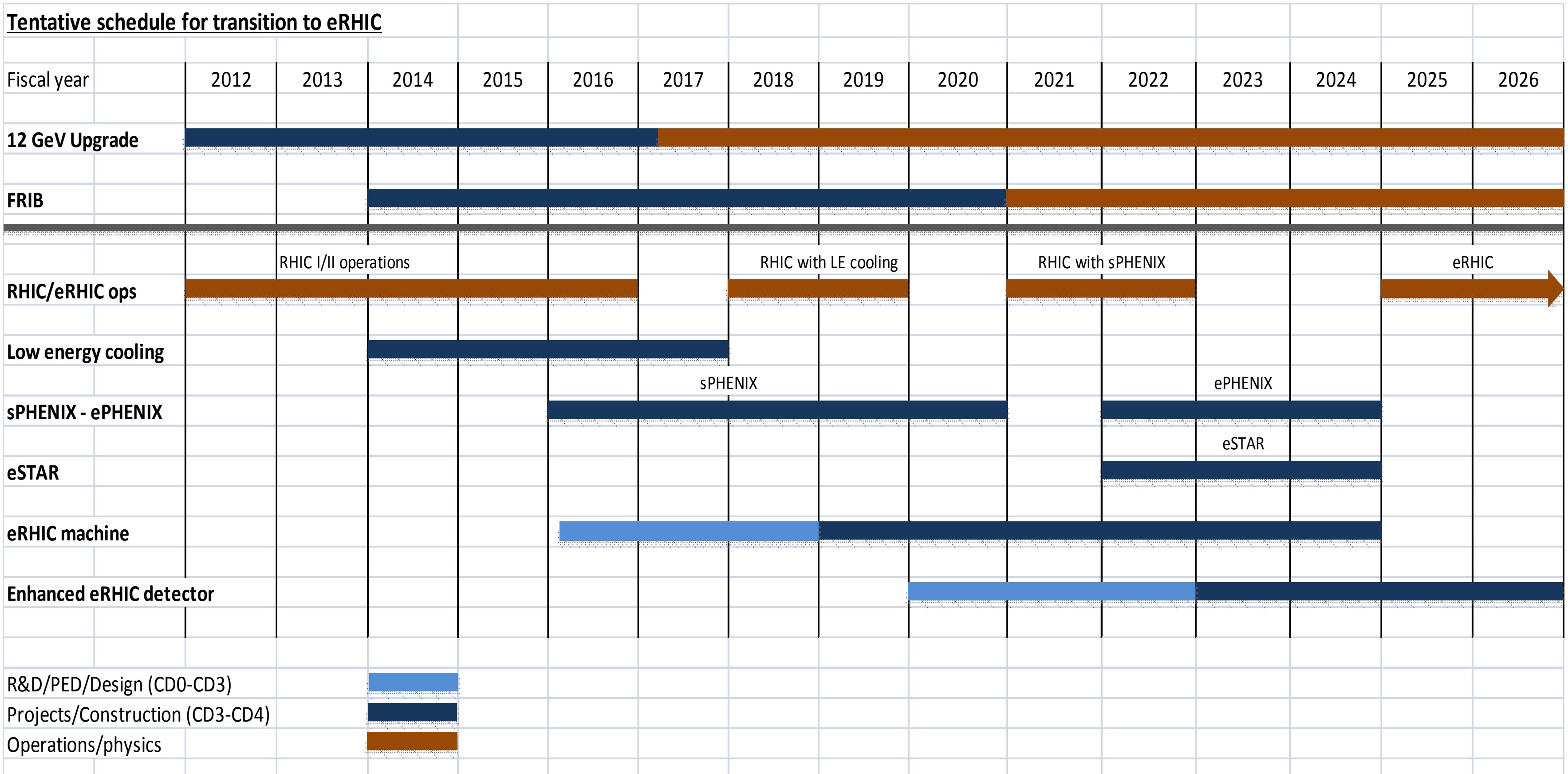
eRHIC Cost Estimate

- Bottom-up cost estimation for eRHIC (5 GeV e-beam) has been done during 2012 (full TPC including ~ 33% average contingency, single IR, not including crab cavities and detector):
  - Cost optimization for layout with 0.83 GeV SRF CW Linac, 4 local recirculation passes for low energy and 2 re-circulating passes in RHIC tunnel:
    FY12$ 530M TPC

- Present design: 15.9 GeV e-beam at > 1 x 10^{33} cm^{-2} s^{-1} and 21.2 GeV e-beam with somewhat less luminosity
  - 1.32 GeV SRF CW Linac, replace 4 small and 2 large recirculation passes with 2 permanent magnet FFAG passes. Scaling from previous above cost:
    FY12$ 550M TPC
  - Including second IR ($50M) and crab cavities for 2 IRs ($100M): FY12$ 700M
  - Escalated to FY14$: ~750M for TPC (not including detectors)

- Plan for new bottom-up cost estimate this year.

eRHIC Schedule



Readiness of eRHIC

- Technology and performance supporting present eRHIC design:
  - 250 GeV polarized proton beams with required intensity and brightness
  - 100 GeV/n Au beams with the required intensity and brightness
  - He-3 beams available from new EBIS
  - 4 mA polarized e beam source demonstrated at Jlab
  - 10 mA ERL demonstrated (Jlab FEL ERL)
  - High energy ERL demonstrated (CEBAF), multi-pass ERL demonstrated (BINP)
  - Performance of existing BNL 704 MHz SRF cavity supports eRHIC linac
  - Crab cavities tested with beam at KEK
  - NS-FFAG principle first demonstrated with EMMA at Daresbury, UK
  - Permanent magnets successfully used for Fermilab Recycler

- Ongoing eRHIC R&D:
  - Prototyping of Gatling Gun polarized electron source
    - *First test with two cathodes this year, prototype supports full tests with 20 cathodes*
  - Strong cooling of hadron beams to ~ 0.2 μm
    - *Coherent electron Cooling is best concept and needs R&D; CeC PoP in 2015/16 using 40 GeV/n Au beams in RHIC*
  - High average current ERL to support operation with high current e-beam
    - *Results from test-ERL in 2014/15*
  - Prototype eRHIC ERL with Gatling Gun and FFAG arcs
    - *Proposed to be built using Laboratory PD funds*
  - Development of high gradient crab cavities within LARP (for HL-LHC upgrade)
  - Development of polarized He-3 underway in collaboration with MIT

Summary

- Linac-ring design of eRHIC with new, cost-effective design reaches high luminosity (> 10^{33} cm^{-2} s^{-1}) up to 125 GeV CM energy and 145 GeV CM energy for somewhat lower luminosity.
- Uses existing RHIC facility for HI and polarized proton beam ($2.5B replacement value) and existing RHIC tunnel and cryo-facility for e-beam.
- R&D under way on high current polarized electron source (Gatling Gun), strong hadron cooling (Coherent electron Cooling) and high current ERL.
- Very preliminary cost estimate: FY14$ 750M (2 IRs, Crab crossings, no detectors)
- Modest upgrades to the hadron ring would support highest luminosity (10^{34} cm^{-2} s^{-1}).

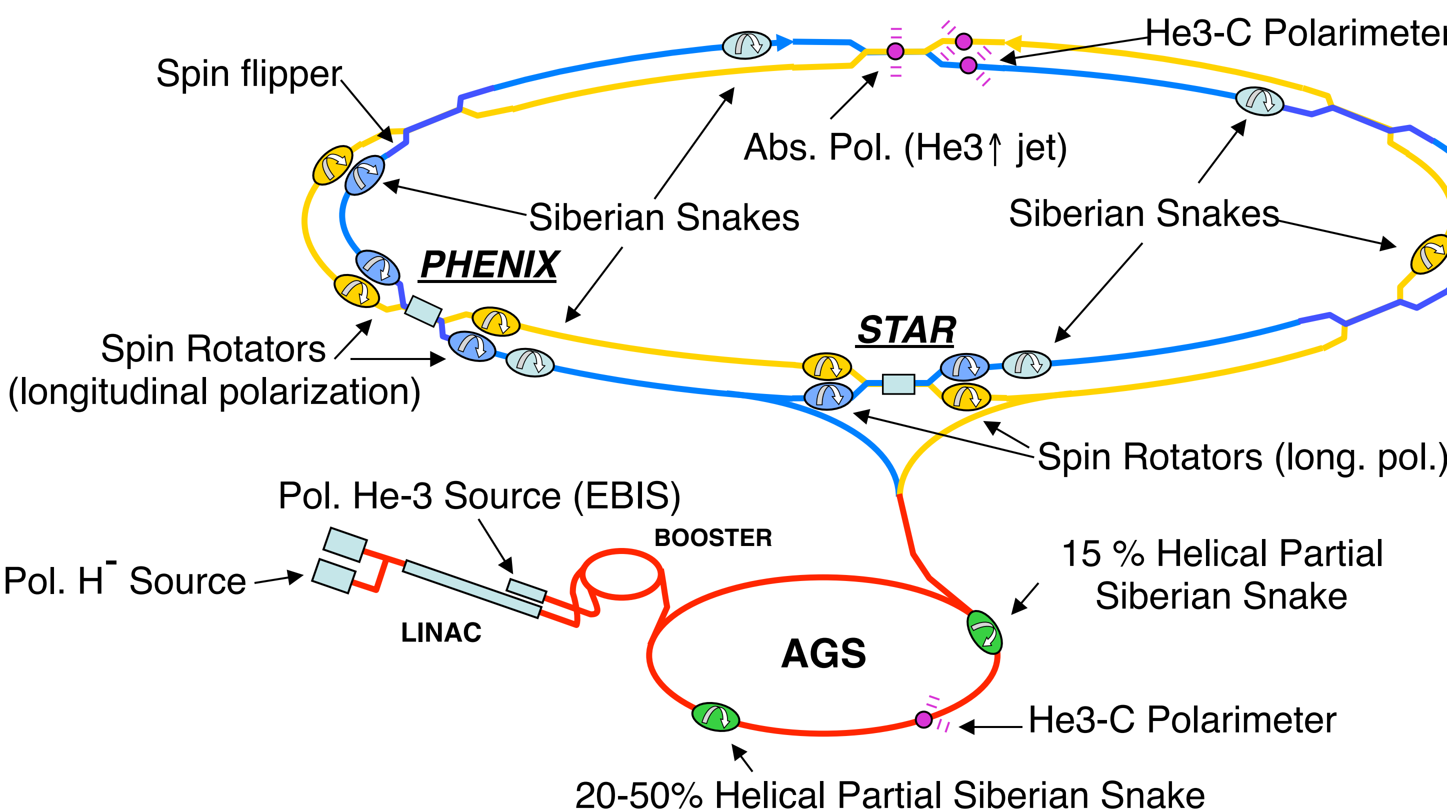
Back-up slides

Recent Reviews

- C-AD Machine Advisory Committee review of eRHIC design (11/2013)
  - J. Jowett (CERN), SY Lee (Indiana), G. Neil (TJNAF), K. Saito (MSU), V. Shiltsev (FNAL), P. Spiller (GSI), R. Talman (Cornell), F. Zimmermann (CERN, Chair)
- CeC Proof-of-Principle review (12/2012)
  - O. Brüning (CERN), H. Padamsee (Cornell), R. Palmer (BNL), V. Lebedev (FNAL, Chair)
- C-AD Machine Advisory Committee review of test-ERL (10/2012)
  - J. Jowett (CERN), G. Krafft (TJNAF), SY Lee (Indiana) K. Ohmi (KEK), V. Shiltsev (FNAL), P. Spiller (GSI), R. Talman (Cornell), F. Zimmermann (CERN, Chair)
- Gatling Gun Advisory Committee review (6/2012)
  - K. Aulenbacher (Mainz, Chair), A. Brachtmann (SLAC), H.-C. Hseuh (BNL), M. Poelker (TJNAF)
- DOE ONP C-AD Accelerator R&D review (12/2011)
  - A. Chao (SLAC), P. Ostrumov (ANL), K. Robinson (LBNL), C. Sinclair (Cornell), J. Delayen (ODU), J. Galayda (SLAC)
- eRHIC design review (8/2011)
  - J. Delayen (ODU), G. Ganetis (BNL), H.-C. Hseuh (BNL),V. Lebedev (FNAL), M. Poelker (TJNAF), E. Pozdeyev (MSU/NSCL), P. Wanderer (BNL), F. Zimmermann (CERN, chair)
- Cost review of medium energy eRHIC design [internal] (10/2009)
  - S. Aronson (Chair), G. Ganetis, M. Harrison, S. Krinsky, M. Marx, P. Pile, M. Schaeffer, S. Vigdor, F. Willeke

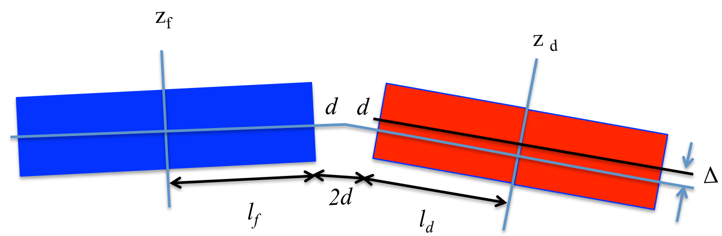
Polarized He-3 in RHIC

- Polarized He-3 from new EBIS; test with unpolarized He-3 started
- Polarimetry:
  - Relative: He3-C CNI polarimeter;
  - Absolute: He3-He3 CNI polarimeter using polarized He-3 jet
- Depolarizing resonances are stronger. However, no depolarization expected with six snakes in RHIC

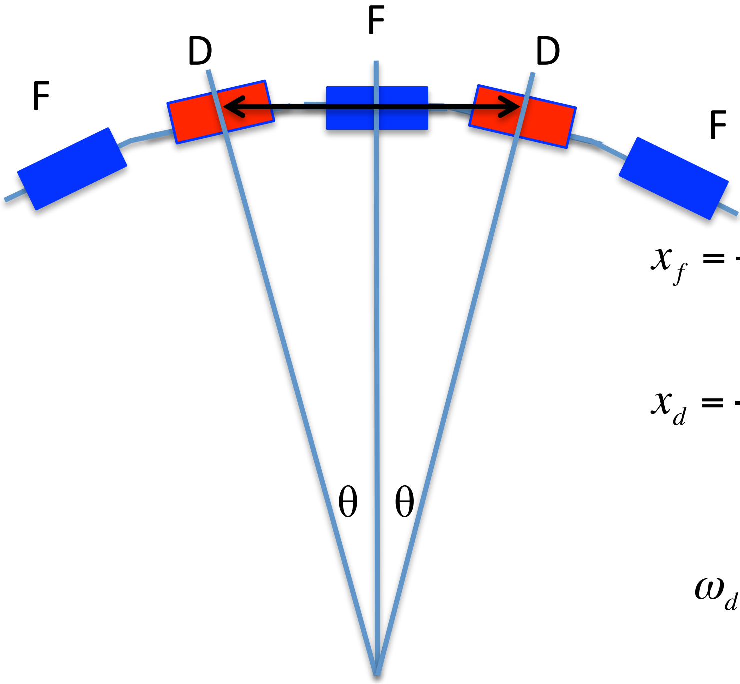


Simple picture of FFAG

- An ideal eRHIC FFAG cell is comprised of two quadrupoles (F & D) whose magnetic axes are shifted horizontally with respect to each other by Δ
- The structure has a natural bilateral symmetry, e.g. all extrema (min and max) are in the centers of the quadrupoles *(independently of any approximation!)*
- Orbit dependence on the energy can be easily found in paraxial approximation
- **Everything can be done accurately and analytically – no doubt that proposed FFAG lattice would work!**



$L=2(l_F+l_D+2d)$



Orbit

$$x_f = -\frac{a_{xd}\theta + c_{xd}\left(\Delta + d\theta\right)}{a_{xf}c_{xd} + a_{xd}c_{xf} + 2dc_{xd}c_{xf}}$$

$$x_d = -\frac{a_{xf}\theta - c_{xf}\left(\Delta - d\theta\right)}{a_{xf}c_{xd} + a_{xd}c_{xf} + 2dc_{xd}c_{xf}}$$

$$a_{xf} = \cos\varphi_f;\ b_{xf} = \frac{\sin\varphi_f}{\omega_f}; c_{xf} = -\omega_f \sin\varphi_f$$

$$a_{xd} = \cosh\varphi_d;\ b_{xd} = \frac{\sinh\varphi_d}{\omega_d}; c_{xd} = \omega_d \sinh\varphi_d$$

$$a_{yf} = \cosh\varphi_f;\ b_{yf} = \frac{\sinh\varphi_f}{\omega_f}; c_{yf} = \omega_f \sinh\varphi_f$$

$$a_{yd} = \cos\varphi_d;\ b_{yd} = \frac{\sin\varphi_d}{\omega_d}; c_{yd} = -\omega_d \sinh\varphi_d$$

$$\omega_d = \sqrt{-\frac{eG_d}{pc}}; \omega_f = \sqrt{\frac{eG_f}{pc}}. \qquad \varphi_{f,d} = \omega_{f,d} l_{f,d}$$